N89-23541

ATOMIC OXYGEN EFFECTS ON SPACECRAFT MATERIALS THE STATE OF THE ART OF OUR KNOWLEDGE

Steven L. Koontz
NASA Lyndon B. Johnson Space Center
Houston, Texas

PRECEDING PAGE BLANK NOT FILMED

SPACE EXPOSURE DATA BASE - ATOMIC OXYGEN EFFECTS ON SPACECRAFT MATERIALS

THREE SPACE SHUTTLE FLIGHT EXPERIMENTS
ONE RECOVERED SATELLITE

Flight	Altitude (Inclin.)	Exposure Time	Fluence* (Attitude)
STS - 5	222 km(28.5°)	44 hours	1×10^{20}(VAR)
STS - 8	222 KM(28.5°)	41.75 hours	3.5×10^{20}(RAM)
STS - 41G	225 km(57°)	38 hours	3×10^{20}(RAM)
SMRM	574 - 491 km	50 months	2×10^{21}(VAR)

* Fluence is in atoms/cm^2

- Detailed descriptions of the flight experiments can be found in References 1 through 21.

SHUTTLE FLIGHT EXPERIMENT ATOMIC OXYGEN EFFECTS DATA BASE

- About 300 different materials have been evaluated and several mechanism studies have been conducted during STS-5, STS-8, and STS-41G.

- Atomic Oxygen Effects were determined by post flight measurements on returned samples; no real time rate data was obtained; only limited variable exposure time data is available.

- Reaction efficiency obtained from flight experiment data provides a measure of material susceptibility to atomic oxygen attack.

    - Reactivity is expressed as the volume or mass of material lost per incident oxygen atom.

    - If the atom fluence is known for a future mission, then surface recession or mass loss can be estimated.

      RECESSION = FLUENCE * REACTIVITY

- Atomic oxygen effects data obtained from Space Shuttle flight experiments can be found in References 1 through 20. Oxidation reactions, not sputtering, are responsible for reactivity.

    - Polymeric materials containing C-H bonds, diamond and graphite have reactivities on the order of 10^{-24} cm^3/atom.

    - Of the metals, only silver and osmium are rapidly attacked by formation of volatile reaction products or surface oxides layers which spall (peel off) readily.

    - Silicones and teflon appear inert.

        - Silicones react to form a protective surface oxide layer (SiO_2).

        - Teflons (pure fluorocarbons) show very low reactivities; The C-F and C-C bonds in these materials appear inert.

    - Surface temperature can influence reactivity.

    - Organic materials show a characteristic surface damage morphology.

REACTION EFFICIENCIES OF SELECTED MATERIALS WITH ATOMIC OXYGEN IN LOW EARTH ORBIT

MATERIAL	REACTION EFFICIENCY, cm^3/ATOM	MATERIAL	REACTION EFFICIENCY, cm^3/ATOM
KAPTON	3×10^{-24}	SILICONES	
MYLAR	3.4	RTV-560	0.2*
TEDLAR	3.2	DC6-1104	0.2*
POLYETHYLENE	3.7	T-650	0.2*
POLYSULFONE	2.4	DC1-2577	0.2*
GRAPHITE/EPOXY		BLACK PAINT Z306	0.3-0.4*
1034C	2.1	WHITE PAINT A276	0.3-0.4*
5208/T300	2.6	BLACK PAINT Z302	2.03*
EPOXY	1.7	PERFLUORINATED POLYMERS	
POLYSTYRENE	1.7	TEFLON, TFE	<0.05
POLYBENZIMIDAZOLE	1.5	TEFLON, FEP	<0.05
25% POLYSILOXANE/45% POLYIMIDE	0.3	CARBON (VARIOUS FORMS)	0.9-1.7
POLYESTER 7% POLYSILANE/93% POLYIMIDE	0.6	SILVER (VARIOUS FORMS)	HEAVILY ATTACKED
POLYESTER	HEAVILY ATTACKED	OSMIUM	0.026
POLYESTER WITH ANTIOXIDANT	HEAVILY ATTACKED		

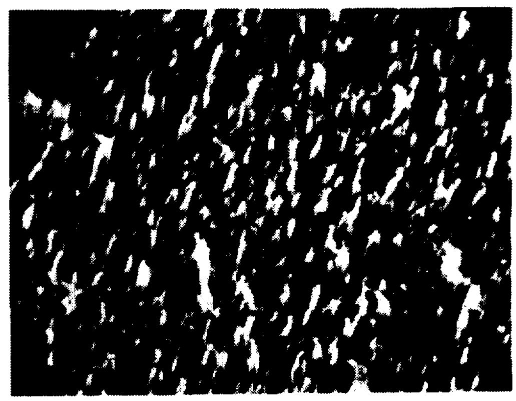
*UNITS OF mg/cm2 FOR STS-8 MISSION. LOSS IS ASSUMED TO OCCUR IN EARLY PART OF EXPOSURE; THEREFORE, NO ASSESSMENT OF EFFICIENCY CAN BE MADE.

SURFACE DAMAGE MORPHOLOGY FROM LEO EXPOSURE

Many organic materials develop a characteristic surface damage morphology ("carpet" morphology) when exposed to atomic oxygen ram flux in low Earth orbit. Fluence dependent changes in the appearance of the carpet have been observed but do not seem to affect the reactivity of the material. At high fluence, the depth of the carpet is much less than the loss in thickness of the material.

COMPARISONS OF STS-8 KAPTON SPECIMENS (12.7 μm) BEFORE AND AFTER ATOMIC OXYGEN EXPOSURE, NORMAL IMPINGEMENT

UNEXPOSED, SEM: 10 000X



EXPOSED, SEM: 10 000X

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

LIMITATIONS OF CURRENT SPACE SHUTTLE FLIGHT EXPERIMENT DATA BASE

- Atom fluences were not measured during flight but calculated using the MSIS model of the thermosphere (Ref. 19); it follows that model errors are included in the flight experiment data base.
- The data base provides only limited basis for understanding the kinetics and mechanism of hyperthermal atom - surface reactions.
- Reaction efficiencies have been obtained at low fluence.
  - STS flights: 10^{19} to 10^{20} atoms/cm^2 in about 40 hours at 222 to 225 km altitude
  - Space Station: 10^{22} to 10^{23} atoms/cm^2 in 30 years (2.6 x 10^5 hours at 340 to 475 km altitude)
- The data base provides only a limited basis for evaluating effects of other space environment factors on oxygen reactivity.
  - Solar ultraviolet (UV) radiation (especially Lyman alpha at 121.6 nmi) and high energy charged particles should influence the magnitude of atomic oxygen effects in some materials through photochemical and radiochemical mechanisms.
  - At 222 km altitude, the high atomic oxygen flux may wash out synergistic effects.
  - Synergistic effects cannot be evaluated with the available data base.
  - No data is available in the polar orbit environment.
- The validity of extrapolation to high fluence conditions or radically different orbital environments is unknown at this time.
  - Components of the Solar Maximum Satellite (altitude 574 to 491 km, inclin. 28.5°) recovered in April 1984 showed surface recession in crude agreement with predictions made using the data base. Teflon appeared to be more reactive than anticipated; kapton reactivity was in agreement with data base (Ref. 20).

LABORATORY SIMULATION AND MODELING OF ATOMIC OXYGEN EFFECTS ON SPACECRAFT MATERIALS

- Ground based simulation and test systems are needed to support (1) interpretation and understanding of environmental effects and (2) development and flight qualification of long life spacecraft materials and components.

- A complete understanding of the kinetics and mechanism of hyperthermal atom surface reactions does not exist. Without the understanding produced by laboratory simulation and modeling studies, we cannot develop accelerated test methods with high confidence, and we cannot understand synergistic effects.

- An ideal laboratory test and simulation system would provide a pure, well collimated beam of neutral oxygen atoms with a kinetic energy of 5 eV (8km/sec) and an atom flux greater than 10^{14} atoms/cm2*sec. No such system exists at this time.

    - Nearly all the neutral atom test methods under development fall into one of four categories.

    1. Thermal atom sources: Oxygen atoms are produced in radio frequency (RF) or microwave discharges to produce high oxygen concentrations at thermal or near thermal energies.

    2. Plasma torch, atomic beam sources: Oxygen atoms are generated in a high temperature plasma; then, free jet or supersonic expansion converts sensible heat to velocity: Atom energies of 1 to 2 eV (possibly 4 eV) have been achieved.

    3. Ion beam methods: Positive or negative atomic ion beams are produced, accelerated, and focused to proper velocity, then neutralized to give a nominal 5 eV oxygen atom beam.

    4. Laser sustained plasma, atomic beam sources: Lasers are used to produce high temperature/high pressure plasmas which expand as free jets or supersonic beams. Atom kinetic energies of 1 to 12 eV have been reported with atom fluxes of 10^{15} to 10^{18} atoms/cm^2*sec.

BEAM SOURCES UNDER DEVELOPMENT

Type	Location, PI	Species	Energy
Ion beam	LeRC, Furgeson	$O^+(O_2)$	0 - 50 eV
Ion beam	JPL, Chutjian Boing, Rempt	O	5 eV
Ion beam	MSFC, Carruth Martin(Denver)	O^+	5 eV
Ion beam	Vanderbilt, Tolk	O^+	100 eV
Ion beam	G.E., Amore	O^+/O_2^+	3 - 10 eV
Ion beam	LeRC, Banks	O^+, O, O_2	3 - 15 eV
Ion beam	Princeton U.	O, O_2, N, N_2	10 eV
Ion beam	Aerospace, Mahadaven	O, O_2, N, N_2	3 - 100 eV
ESD	LaRC, Outlaw	O	5 eV

- All the above sources produce fluxes of less than 10^{14} atoms/cm^2*sec at 5 eV. Those below produce greater fluxes.

Plasma torch, atom beam	UTIAS, Tennyson	O, O_2, He	1 - 4 eV
ECMD, atom beam	Aerospace, Arnold	O, O_2, He	0.2 eV
Plasma torch, atom beam	ARI, Freeman	O, O_2, He	1.3 eV
Laser Disch. atom beam	PSI, Caledonia	O, O_2	2 - 14 eV
Laser Disch. atom beam	LANL, Cross	O, O_2, He	1 - 5 eV
Laser Disch. atom beam	JPL, Brinza	O	2 - 7 eV

LABORATORY SIMULATION AND TEST SYSTEM EVALUATION

- The following data are necessary for a complete evaluation of the test system:

  - Direct measurement of atom flux and velocity

  - Direct measurement of beam purity

  - Reaction efficiency measurements on materials in the flight experiment data base

  - Reaction efficiency measurements on the LeRC "round robin" materials set

- No ideal, completely characterized system exists; however, the laser sustained plasma, atomic beam systems offer the best approximations.

  - Los Alamos National Laboratory (Ref. 21)

    - Continuous beam (CW laser sustained discharge)

    - 1.5 to 5 eV O atoms; 10^{15} to 10^{17} atoms/cm2*sec

    - Beam purity varies; in situ diagnostics measure O_2, inert gas and UV radiation content; ions and electrons and O atom excited states are negligible.

    - Kapton reactivity and surface damage morphology are in reasonable agreement with the flight data base.

    - Teflon appears more reactive than in flight.

  - Physical Sciences Incorporated (Ref. 22)

    - Pulsed beam (Pulsed laser sustained discharge)

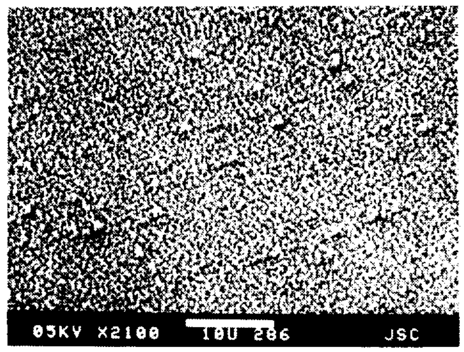
    - 2 to 14 eV O atoms; 10^{15} to 10^{17} atoms/cm^2*sec (instantaneous fluxes much higher, about 10^{21})

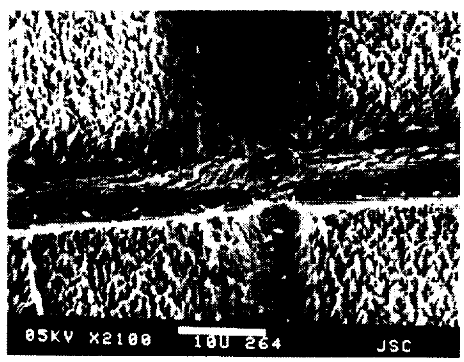
    - Beam purity measured with in situ diagnostics; 98% O atoms, negligible UV, ions, electrons, and O_2; O atom excited states negligible

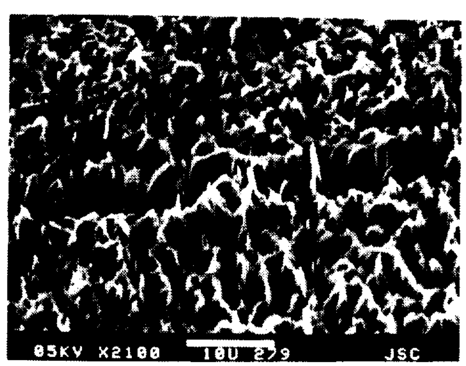
    - Kapton and teflon reactivities and surface damage morphology in reasonable agreement with flight data base

SURFACE DAMAGE MORPHOLOGY FROM LANL BEAM

Samples of organic materials exposed to the atomic oxygen beam at Los Alamos National Laboratory (LANL) develop carpet morphology similar to that developed in low Earth orbit. As the three SEM images shown below demonstrate, the appearance of the carpet depends on the fluence. From top to bottom these samples experienced 7.2×10^{19}, 1.4×10^{20}, and 4.0×10^{20} atoms/cm^2. The atom flux was 8×10^{15} atoms/cm^2 sec with a nominal atom kinetic energy of 1.5 eV.







ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

SUMMARY

- In flight materials exposure data base
    - Extensive quantitative data is available from limited exposures in a narrow range of orbital environments.
    - More data is needed in a wider range of environments as well as longer exposure times.
        - Synergistic effects with other environmental factors
        - Polar orbit and higher altitude environments
        - Real time materials degradation data is needed to understand degradation kinetics and mechanism
- Laboratory simulation and modeling
    - Almost no laboratory data from high fidelity simulations of the LEO environment; simulation and test system under development; data base scanty
    - Theoretical understanding of hyperthermal atom surface reactions in the LEO environment not good enough to support development of reliable accelerated test methods
    - The laser sustained discharge, atom beam sources are the most promising high fidelity simulation-test systems at this time

REFERENCES

1. Leger, L.J. Oxygen Atom Reaction With Shuttle Materials at Orbital Altitudes, Nasa TM-58246, May 1982.

2. Leger, L.J. Visentine, J.T., and Schliesing, J.A., A Consideration of Atomic Oxygen Interaction with Space Station, AIAA Paper 85-0476, AIAA 23rd Aerospace Sciences Meeting, Reno, Nevada, January 14-17, 1985.

3. Leger, L.J., et al., STS Flight 5 LEO Effects Experiment - Background Description and Thin Film Results, AIAA Paper 83-2631, AIAA Shuttle Environment and Operations Meeting, Washington, DC, October-November 1983.

4. Whitaker, A.F., et al., LEO Oxygen Effects on Spacecraft Materials, AIAA Paper 83-2632, AIAA Shuttle Environment and Operations Meeting, Washington, DC, October-November 1983.

5. Park, J.J., et al., Effects of Atomic Oxygen on Paint and Optical Coatings, AIAA Paper 83-2634, AIAA Shuttle Environment and Operations Meeting, Washington, DC, October-November 1983.

6. Zinner, E., et al., Erosion of Mylar and Protection by Thin Metal Films, AIAA Paper 83-2636, AIAA Shuttle Environment and Operations Meeting, Washington, DC, October-November 1983.

7. Liang, R. and Gupta, A., Mechanistic Studies of Kapton Degradation in Shuttle Environments, AIAA Paper 83-2656, AIAA Shuttle Environment and Operations Meeting, Washington, DC, October-November 1983.

8. Visentine, J. T., et al., STS-8 Atomic Oxygen Effects Experiment, AIAA Paper 85-0415, AIAA 23rd Aerospace Sciences Meeting, Reno, Nevada, January 14-17, 1985.

9. Whitaker, A.F., Orbital Atomic Oxygen Effects on Thermal Control and Optical Materials STS-8 Results, AIAA Paper 85-0416, AIAA 23rd Aerospace Sciences Meeting, Reno, Nevada January 14-17, 1985.

10. Banks, B.A., et al., Ion Beam Sputter-Deposited Thin Film Coatings for Protection of Spacecraft Polymers in Low Earth Orbit, AIAA Paper 85-0420, AIAA 23rd Aerospace Sciences Meeting, Reno, Nevada January 14-17, 1985.

11. Liang, R.H., and Gupta, A., Mechanistic Studies of Interaction of Materials With Energetic Oxygen Atoms in Low Earth Orbit, AIAA Paper 85-0422, AIAA 23rd Aerospace Sciences Meeting, Reno, Nevada January 14-17, 1985.

12. Gull, T.R., et al., Effects of Optical Surfaces at Shuttle Altitudes, AIAA Paper 85-0418, AIAA 23rd Aerospace Sciences Meeting, Reno, Nevada January 14-17, 1985.

13. Gregory, J.C. and Peters, P.N., Measurement of Reaction Rates and Activitation Energies of 5 eV Oxygen Atoms With Graphite and Other Solid Surfaces, AIAA Paper 85-0417, AIAA 23rd Aerospace Sciences Meeting, Reno, Nevada, January 14-17, 1985.

14. Smith, K., Evaluation of Oxygen Interaction with Materials (EOIM) - STS-8 Atomic Oxygen Effects, AIAA Paper 85-7021, AIAA Shuttle Environment and Operations II Conference, Houston, Texas, November 1985.

15. Whitaker, A.F., et al., Protective Coatings for Atomic Oxygen Susceptible Spacecraft Materials - STS41-G Results, AIAA Paper 85-7017, AIAA Shuttle Environment and Operations II Conference, Houston, Texas, November 1985.

16. Fromhold, A.T., et al., Reaction of Metals in Lower Earth Orbit During Space Shuttle Flight 41-G, AIAA Paper 85-7018, AIAA Shuttle Environment and Operations II Conference, Houston, Texas, November 1985.

17. Zimcik, D.G. and Maag, C.R., Results of Apparent Atomic Oxygen Reactions With Spacecraft Materials During Shuttle Flight STS41-G, AIAA Paper 85-7020, AIAA Shuttle Environment and Operations II Conference, Houston, Texas, November 1985.

18. Peters, P.N., Gregory, J.C., and Swann, J.T., Effects on Optical Systems From Interactions With Oxygen Atoms in Low Earth Orbits, Applied Optics, Vol. 25, No. 8, April 15, 1986.

19. Visentine, J.T. and Leger, L.J., Material Interactions With the Low Earth Orbital Environment: Accurate Reaction Rate Measurements, AIAA Paper 85-7019, AIAA Shuttle Environment and Operations II Conference, Houston, Texas, November 1983.

20. Proceedings of the SMRM Degradation Study Workshop. The Satellite Servicing Project, Goddard Space Flight Center 408-SMRM-79-0001, May 9-10, 1985.

21. Visentine, J.T. and Leger, L.J., Atomic Oxygen Effects Experiments: Current Status and Future Directions, NASA TM, JSC, May 18, 1987.

22. Caledonia, G.E., Krech, R.H., and Green, B.D., A High Flux Source of Energetic Oxygen Atoms for Material Degradation Studies, AIAA J. 25, 59 (1987); also Caledonia, G.E., and Krech, R.H., Energetic Oxygen Atom Material Degradation Studies, AIAA-87-0105, 25th Aerospace Sciences Meeting, Reno, Nevada, January 1987.